Fecal sludge as a fuel: characterization, cofire limits, and evaluation of quality improvement measures

Lauren M. Hafford, Barbara J. Ward, Alan W. Weimer and Karl Linden

ABSTRACT

In many low-income cities, a high proportion of fecal sludge, the excreta and blackwater collected from onsite sanitation systems such as pit latrines, is not safely managed. This constitutes a major danger to environmental and human health. The water, sanitation, and hygiene sector has recognized that valorization of treated fecal sludge could offset the upfront cost of treatment by using it as a fuel source. The few quantitative studies on fecal sludge fuel published to date have focused on heating value, moisture, ash fraction, and heavy metals. However, other factors impacting fuel utility, specifically ash speciation, have not been adequately quantified for fecal sludge. This study contributes to closing that gap and shows the value of more detailed quantification. It first characterizes fecal sludge samples from Colorado and Uganda, confirms that the fuel is better if cofired with other biomass, and outlines a framework for determining safe cofire ratios. Second, the study evaluates two methods for improving fecal sludge as a fuel: carbonization and ash leaching. Carbonization of fecal sludge did not improve fuel quality, but leaching showed promise in ash reduction.

Key words | ash, corrosion, fecal sludge, fouling, pyrolysis, slagging

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INTRODUCTION

Globally, 2.7 billion people rely on unsewered sanitation systems (Strande *et al.* 2014). This population comprises not only inhabitants of rural areas, but also the majority of urban dwellers in low- and middle-income countries (Peal *et al.* 2014). Most developing cities have insufficient infrastructure to manage and treat the fecal sludge, defined as excreta and blackwater, with or without greywater, accumulated in onsite sanitation facilities such as pit latrines and septic tanks (Strande *et al.* 2014). As a result, on average more than three quarters of fecal sludge is not safely treated, but is released into the urban environment, posing a serious threat to human health and environmental safety (Blackett *et al.* 2014). Fecal sludge treatment can be made more economically sustainable by developing a market for treatment products. There is high demand for affordable biomass

fuels in many African cities (Diener *et al.* 2014). Dried fecal sludge is an appealing biomass fuel for industrial kilns, as its availability does not fluctuate seasonally, and it does not have an established market value (Ward *et al.* 2017). Some companies market dried fecal sludge as a solid fuel: the container-based sanitation model of Sanivation in Naivasha, Kenya, produces briquettes from feces and carbonized biomass (www.sanivation.com).

Solid biofuels and coals are characterized by standard methods before being adopted into pilot and industrial scale use, such as stand-alone combustion, cofiring or (co-)gasification setups. This study will not review in detail the vast literature on strategies relevant to using biomass as a coal equivalent (Miles *et al.* 1995; Jenkins *et al.* 1998; Demirbas 2003; Saidur *et al.* 2011). Instead, it draws upon that literature to identify the discrete fuel characteristics significant in fuel utility, and compares the performance of fecal sludge to biomass for these characteristics. Calorific value represents the main economic value of thermal fuels. Ash and moisture are valueless; high contents increase transportation costs and

reduce combustion efficiency. Ultimate and proximate analyses indicate fuel performance, NO_X, and SO_X emissions. Ash speciation reveals the types of inorganic chemical interactions to be expected in the boiler or kiln.

Although biomass co-combustion decreases CO_2, NO_X, and SO_X emissions in boilers and gasifiers (Demirbas 2003) compared to coal, complex reactions between certain inorganic compounds in fuel ash can result in slagging and fouling deposits on heat transfer surfaces (Miles *et al.* 1995; Baxter *et al.* 1996; Jenkins *et al.* 1998; Pronobis 2005; Saidur *et al.* 2011). Biomass is especially prone to deposition because alkali and alkaline-earth metals, especially sodium and potassium, are powerful fluxes for alumino-silicate systems (Fernando 2012). During combustion, the forms of potassium and sodium found in biomass are susceptible to vaporization, and undergo numerous reactions, depending on the availability of sulfur, chlorine, silicon, and other elements (Jenkins *et al.* 1998; Shao *et al.* 2012). In particular, the alkali and alkaline earth metals can create vapor phase chloride compounds, depositing as a sticky layer on the heat exchanging and heat transfer surfaces, leading to ash layer growth. The alkali compounds can also react with the silica in the fly ash during combustion, creating alkali silicate deposits on reactor walls (Shao *et al.* 2012). These deposits can retard heat transfer, reducing combustor thermal efficiency and capacity, and can lead to increased maintenance outages and costs (Miles *et al.* 1995; Shao *et al.* 2012). Both sulfur and phosphorus in the flue gas can mitigate these effects by reacting with the alkali compounds, increasing their melting temperatures and reducing deposition (Nielsen *et al.* 2000; Shao *et al.* 2012).

The risks to environmental and public health from untreated fecal sludge are high, but new environmental issues from the combustion of fecal sludge should be considered before implementing. The environmental risks of combusting sewage sludge have been studied, and include heavy metals, dioxins and furans, NO_x, N_2O, SO_2, and $HCl/HF/C_xH_y$ (Werther & Ogada 1999). Heavy metal concentrations in sewage sludge are linked to industrial activity in the catchment (Werther & Ogada 1999), and indeed one study found heavy metal concentrations in fecal sludge to be generally lower than both sewage sludge and industrial combustion guidelines (Gold *et al.* 2017). Industrial use has been recommended over domestic use, as centralized combustion allows for sufficient emissions control and safe handling measures (Gold *et al.* 2017; Ward *et al.* 2017).

While sewage sludge has been extensively evaluated as a solid fuel, fecal sludge has only recently been considered for its solid fuel potential. It cannot be assumed that sludge from wastewater treatment and sludge from onsite sanitation systems are comparable. Fecal sludge arrives batchwise at treatment facilities after having been stored under a wide range of conditions for weeks to years. This leads to orders of magnitude variations in solids content, extent of degradation, and level of inorganic material (sand, soil, or garbage) (Bassan *et al.* 2013; Gold *et al.* 2016; Semiyaga *et al.* 2017). To date, the research on using fecal sludge has not been detailed enough to quantify its capabilities as a solid fuel. Calorific value, moisture and ash content, ultimate and proximate analyses, and heavy metals content have been evaluated, and several pilot-scale combustion tests exist in the literature (Muspratt *et al.* 2014; Tukahirwa *et al.* 2016; Ward *et al.* 2017; Gold *et al.* 2017). The ash content of fecal sludge was found to be considerably elevated compared with feces, biofuels and coal (Gold *et al.* 2017; Ward *et al.* 2017). However, insufficient research exists on ash speciation, which impacts slagging, fouling, and boiler operation, and on chlorine, which affects corrosion and emissions.

Methods for reducing ash fraction and increasing calorific value of fecal sludge derived fuels have been discussed, but not implemented at large scale. Dewatering using geotextiles can reduce ash content in dry fecal sludge compared to sand drying beds by eliminating contact between sludge and the sand layer; co-processing with available waste biomass can maximize energy recovery while minimizing ash (Ziebell *et al.* 2016; Ward *et al.* 2017). Low temperature carbonization increases the calorific value of urine diverted feces (Ward *et al.* 2014) but pyrolyzing fecal sludge may concentrate the ash fraction (Ward *et al.* 2017). Ash removal through leaching has not been investigated for fecal sludge.

This study performed ultimate and proximate analysis and ash speciation on feces and fecal sludge. The potential for slagging and fouling was explored, and a simple model for predicting appropriate cofire ratios for fecal fuels and biomass is presented. Carbonization and ash leaching were investigated as methods to improve fuel quality.

METHODS

Fecal sample collection

Fecal sludge is highly variable in consistency and composition (Strande *et al.* 2014). A small study cannot span this variability, but an attempt was made to include a few different sources and holding conditions. Samples in this research came from two pit latrines in Boulder, CO, USA, three

vacuum trucks of fecal sludge in Kampala, Uganda, and urine-diverted feces from 10 volunteers in Boulder. Fecal sludge samples Boulder 1 and Boulder 2 were collected directly from pit latrines by lowering an aluminum scoop on a long handle into the sludge approximately 30 cm below the surface. They were processed directly after collection. Fecal sludge samples Kampala 1, Kampala 2, and Kampala 3 were collected from three vacuum trucks during discharge at the National Water and Sewerage Corporation Lubigi Fecal Sludge Treatment Plant using the protocol described in Gold *et al.* (2017). Samples were completely dried in an oven at 105 °C before shipping to the University of Colorado Boulder for analysis. Urine-diverted fecal matter was collected from approximately 10 volunteers at the University of Colorado Boulder. Feces were captured in plastic bags and remained at room temperature for up to 24 h, before being stored at −20 °C for up to one month. Collected feces were homogenized into one sample before analysis. Identifying information about volunteers was not gathered, including diet.

Fuel characterization and ash analysis

The Boulder samples (fecal sludge and feces) were dried in Pyrex baking trays in a Thermo Scientific Lindberg Blue M heavy duty box furnace at 105 °C. Sub-samples were carbonized in covered ceramic crucibles at 300 °C with a 3 °C/min ramp rate and 2 h dwell. Internal temperature of the feces was monitored with a thermocouple and temperature data logger during drying and carbonization. All Kampala samples (1, 2, and 3) were dried in a 105 °C drying oven. All samples were pulverized and homogenized before analysis.

Samples were tested for higher heating value (HHV), ash speciation, ash fusion, ultimate analysis, and proximate analysis according to the matrix in Table 1. The HHV is the amount of heat released during combustion, and is tested by bomb calorimetry. Ash speciation determines the relative concentrations of the dominant elements in the ash, and is reported as oxides. Ashed samples were digested in hydrofluoric acid and aqua regia, and were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES). Ultimate analysis fractions the fuel into carbon, hydrogen, nitrogen, sulfur, and oxygen (determined by subtraction), and proximate analysis fractions the fuel into moisture, volatile matter, fixed carbon, and ash. Both were performed to predict fuel performance and emissions, and are reported as percent mass on a dry basis.

Ash leaching was performed by the Baxter procedure (Miles *et al.* 1995) wherein fuels are leached sequentially with water, 1 M ammonium acetate, and 1 M hydrochloric acid to determine the soluble fractions of the ash. Solvents were prepared at room temperature with Milli-Q water and analytical-grade chemicals. After leaching, a portion of the remaining fuel at each step was ashed and the weight fraction of ash in the fuel was measured. For the resultant fuel after each leaching step, the HHV was calculated assuming ash has no caloric value:

$$HHV_r = HHV_u + HHV_u \cdot (A_u - A_r) \tag{1}$$

where HHV is the higher heating value of the fuel in MJ/kg, A is the mass fraction (dimensionless) of ash in the fuel, r denotes resultant fuel and u denotes unleached fuel.

Table 1 | Test matrix

Origin	Boulder						Kampala		
	Feces		1		2		1	2	3
Sample ID Preparation	Dry	Char	Dry	Char	Dry	Char	Dry	Dry	Dry
Ashing (ASTM E1755 – 01)	•	•	•	•	•	•	•	•	•
HHV[a] (ASTM D5865)	•	•	•	•	•	•	•	•	•
Ash fusion[a] (ASTM D1857)	•	•	•	•	•	•	•	•	•
Ultimate analysis[a] (ASTM D3176)	•	•	•	•	•	•			
Proximate analysis[a] (ASTM D3172)	•	•	•	•	•	•			
Ash speciation (ASTM D6357 – 11)	•		•		•		•	•	•
Ash leaching (Baxter procedure)[b]	•		•		•		•	•	•

[a]Analysis performed by Hazen Research, Inc. (Golden, CO, USA).
[b]Miles *et al.* (1995).

Model for cofiring fecal fuels

The cofiring of fecal fuels with default fuels (coal or common biomass such as bagasse, sawdust, or coffee husk) was investigated. Benchmark coal data came from Steyn & Minnitt (2010), and biofuel data came from the Phyllis2 Database for Biomass and Waste (https://www.ecn.nl/phyllis2) (Phyllis2). Multiple samples were selected to create category averages, and details of these selections are available in the Appendix (available with the online version of this paper). Miles *et al.* (1995) calculated the alkali index (kg alkali/GJ) of a pure fuel as:

$$AI = \frac{1}{Q} \cdot A \cdot (K_2O + Na_2O) \tag{2}$$

where Q is the HHV in GJ/kg, A is the dimensionless mass fraction ash in the dry fuel, and K_2O and Na_2O are the dimensionless mass fractions of the oxides in the ash. The AI of a blended fuel is the AI of the constituent fuels multiplied by the mass fraction they represent. Solving for the mass fraction of the biofuel gives:

$$Y_b = \frac{AI_T - AI_d}{AI_b - AI_d} \tag{3}$$

where Y_b is the dimensionless mass fraction of the biofuel in the blend, d and b denote default and biofuels, respectively, and AI_T is any targeted value for the AI. Suggested upper limits of the AI are 0.17 kg alkali/GJ for low risk and 0.34 kg/GJ for high risk (Miles *et al.* 1995). Recommended cofire ratios are the mass fractions of biofuels for which the calculated alkali index of the fuel mixture is at the upper limits. The model was written in Python 2.7.12 and is available upon request.

To model cofire limits for fecal fuels, only the alkali index was used, instead of a composite including other common indices such as the base-to-acid ratio (B/A) or the slagging index *RS* (Winegartner 1974; Pronobis 2005). These indices consider the elemental composition of the ash but not the overall ash fraction, and thus their applicability is unknown when applied to fuels with upwards of 50% ash.

RESULTS AND DISCUSSION

First, results of fuel characterization are presented, and the implications for the value of fecal sludge as a solid fuel are discussed. Second, results of ash elemental analysis are presented, and their implications in slagging and fouling are discussed. Third, chlorine results are presented, and potential for corrosion is discussed. Last, results of the fuel improvement measures are presented, and their efficacy is evaluated.

Fuel characterization

The energy and ash characterization results are reported in Table 2, with fecal and sewage sludge data from the literature. Literature biofuel data are available in Table A1 in the Appendix (available with the online version of this paper).

The fecal sludge in this study has lower HHV (10–16 MJ/kg) than typical biomass (18–20 MJ/kg) (Phyllis2), but is in the range of other fecal sludge and sewage sludge data. It is worth noting that there is significant variability for HHV in fecal sludge (see Figure A1 in the Appendix, available online). The energy content of urine-diverted dry feces (20.0 MJ/kg) is comparable to biomass. While the calorific value of fecal sludge is lower than biomass fuels, it can still provide net benefit during combustion.

Ash is the inert, inorganic fraction of the fuel, and is valueless. Ash in feces comes from indigestible nutrients, such as vitamins (Rose *et al.* 2015). Additionally, pits are prone to ingress of sand and dirt, through the drop hole or through the sidewalls of a partially or poorly lined pit (Seck *et al.* 2015). Ash does not contribute to the heating value, and higher ash content is consistent with lower calorific value. The ash in the fecal sludge samples of this study was very high, 25–50% dry solids (ds), compared to sewage sludge (22%ds) and other biomass (typically less than 10%ds). This is one possible explanation for the lower HHV of fecal sludge compared to feces, sewage sludge, and biomass. The high ash content of fecal sludge impacts its value as a fuel by reducing the HHV and increasing slagging and fouling (see the Ash elemental analysis section). Storage time was not a controlled variable in this study, but it has been suggested that the ash fraction of fecal sludge will increase during extended storage time, as the organic matter degrades and is released as gases (Still & Foxon 2011). Variability in storage time could account for the wide variation in HHV for fecal sludge observed in this study and reported in the literature.

The ultimate and proximate analyses can give an indication of the general thermal and emission performance of solid fuels. The results are reported in Table 3, alongside comparison fecal and sewage sludge data from the literature.

In fuels, sulfur and nitrogen are responsible for SO_X and NO_X emissions of boilers, and reduction in these emissions is one of the recognized benefits of biofuels (Baxter 2005;

Table 2 | Energy and ash characterization of dried feces and fecal sludge

Origin	Boulder			Kampala				
Sample ID	Feces	1	2	1	2	3	Fecal sludge	Sewage sludge[e]
Energy content (MJ/kg)								
HHV	20	10.4	14.6	14.7	15.5	12.8	10.9–19.1[a,b,c,d]	13.5 ± 1.5
Ash content (%ds)								
Ash	13.5*	51.2*	36.8*	37.9	36.6	27.4	47.0–58.7[a]	41.3 ± 8.9
Ash elemental analysis (% ash)								
P_2O_5	41.0*	27.0*	30.6*	17.2	17.2	16.9		13.8 ± 7.2
MnO	2.0*	1.1*	1.0*	0.1	0.1	0.2		
Fe_2O_3	0.5*	1.2*	0.7*	2.1	1.9	2.7		14.0 ± 8.2
MgO	8.9"	6.6*	5.6*	6.8	6.7	12.1		2.2 ± 0.8
SiO_2	3.6*	10.8*	4.3*	15.8	13.2	18.9		32.5 ± 7.7
Al_2O_3	0.3*	3.3*	1.2*	5.2	4.9	6.1		11.9 ± 3.8
CaO	20.5*	18.0*	22.4*	9.1	8.7	12		12.8 ± 6.1
TiO_2	0.0*	0.3*	0.3*	0.3	0.3	0.4		0.9 ± 0.4
Na_2O	2*	9.9*	9.9*	10.2	12	6.6		1.5 ± 1.6
K_2O	18.3*	14.2*	11.6*	16.9	18.7	8.2		1.5 ± 0.8
Alkali index (kg alkali/GJ)								
Alkali index	1.4	11.9	5.4	7	7.2	3.2		0.9
Chlorine content (%ds)								
Chlorine	0.1	7	8.8	-	-	-	0.04–0.14[a]	0.2 ± 0.8

*Mean values, $n = 3$; otherwise $n = 1$ for data in this study. Sewage sludge $n = 7$–44. Undetermined values indicated by '-'. Ash and chlorine are reported as mass percent of dry solids (%ds); ash speciation is reported as mass percent of the ash.
Literature data from [a]Gold *et al.* (2017), [b]Muspratt *et al.* (2014), [c]Byrne *et al.* (2015), [d]Seck *et al.* (2015), [e]Phyllis2.

Table 3 | Ultimate and proximate analysis of feces, fecal sludge, and sewage sludge

Origin	Boulder			Fecal sludge[a]		
Sample ID	Feces	1	2	Kampala	Dakar	Sewage sludge[b]
Proximate analysis (%ds)						
Fixed carbon	10.2	6.2	0.4			11.8 ± 6.6
Volatile matter	74.2	42.7	61.1			58.5 ± 5.0
Ultimate analysis (%ds)						
Carbon	49.7	27.1	37	27.8 ± 3.1	28.8 ± 3.4	30.5 ± 3.7
Oxygen	22.4	14.8	15.8			30.1 ± 6.6
Hydrogen	6.2	3.5	4.9	4.2 ± 0.5	4.2 ± 0.4	6.3 ± 0.7
Nitrogen	5	2.5	2.9	3.2 ± 0.4	3.0 ± 0.6	7.0 ± 1.7
Sulfur	0.9	0.8	0.8	0.7 ± 0.1	1.7 ± 0.0	1.8 ± 0.7

Elemental composition is reported as mass percent of dry solids (%ds). $N = 1$ for data in this study; $n = 38$–47 for sewage sludge. Literature data from [a]Gold *et al.* (2017), [b]Phyllis2 database.

Darvell *et al.* 2010; Fernando 2012). The nitrogen contents of these fecal sludge samples are higher than South African coal and biomass, and lower than sewage sludge. The sulfur contents are lower than South African coal and sewage sludge, even though they are higher than comparison biomasses. These findings are consistent with previous

characterizations of fecal sludge in sub-Saharan Africa (Gold *et al.* 2017).

Compared to biomass, fecal sludge has a reduced calorific value, higher ash content, and more sulfur and nitrogen. On this basis alone, its quality as a solid fuel is modest. Feces have a higher calorific value and less ash, making it a more competitive solid fuel.

Ash elemental analysis

The ash composition of fecal fuel is distinctly different from typical biomass and sewage sludge (Figure 1). Sodium and potassium oxides were very high in fecal sludge, especially compared to biomass. There are orders of magnitude more phosphorus in the fecal sludge in this study and sewage sludge, compared to biomass.

For the fuels in this study, the calculated alkali indices were high (1.4–11.9 kg Alkali/GJ), due to the high Na and K content. This is well outside the high-risk limit (0.34), above which 'the fuel is virtually certain to slag and foul to an unmanageable degree' (Miles *et al.* 1995). To get value out of fecal sludge-based fuels, cofiring with lower-alkali fuels is advisable.

This study developed a simple model to calculate safe cofire ratios for fecal fuels, according to the alkali index. The model calculates the ratio of biofuels (fecal fuels, bagasse, coffee husk) added to default fuels (coal, sawdust), for which the alkali index is at the limits. Fuels must have an alkali index of <0.34 kg/GJ to be applied as a default fuel. The model requires the following data for the fuels: HHV, Ash (%ds), K_2O (%ash), and Na_2O (%ash). The output of the model is permissible cofire ratios (for low and high risk of fouling). Figure 2 shows the output when firing with sawdust.

The model shows that the fecal sludge from this study cannot be fired in even moderate concentrations before the alkali index low-risk limit is reached (1–5% mass fraction fecal sludge; 12% for feces). This is mainly due to higher Na and K concentrations compared to biomass or sewage sludge. The model was also run with South African coal as the base fuel; the output is similar to the sawdust output, and is available in the Appendix (Figure A3, available online).

Interestingly, these findings correlate with the observations in Tukahirwa *et al.* (2016), who were running small-scale cofiring tests, with fecal sludge + coffee husk, bagasse, or sawdust. They observed that pellets made of
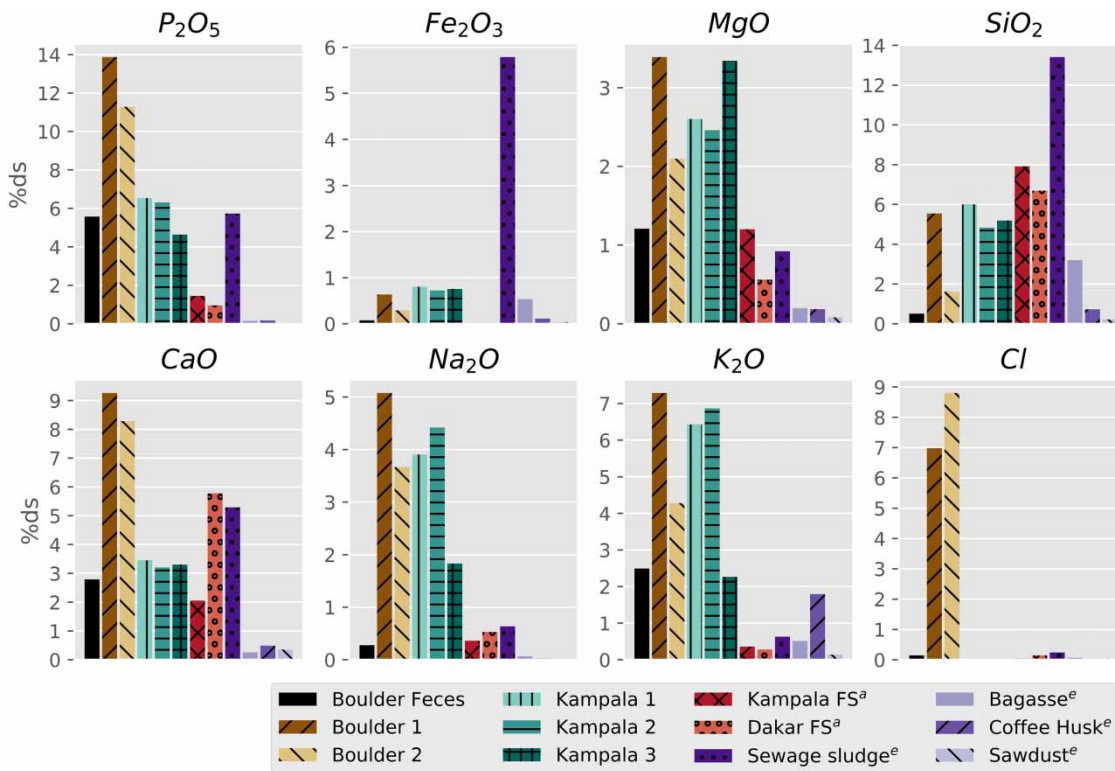

Figure 1 │ Ash speciation of fecal fuels and comparison biofuels, reported as weight percent of the oxide in fuel dry solids. *Sources:* [a]Gold *et al.* (2017), [e]Phyllis2.
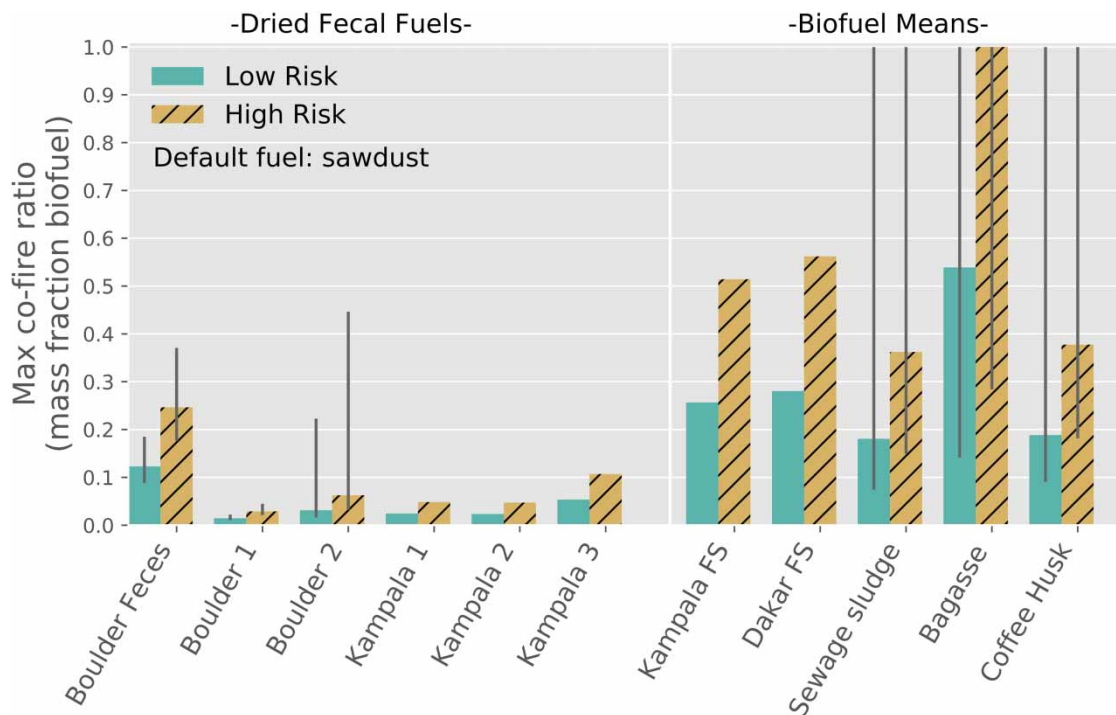
Figure 2 | Permissible cofire ratios of additional biofuels when blended with sawdust. Green bars indicate cofire ratio with low risk of slagging and fouling, where the alkali index of the mixture (AI$_M$) is less than 0.17 kg alkali/GJ fuel. Orange bars indicate ratios with high risk, where AI$_M$ exceeds 0.34 kg/GJ. Error bars indicate 1 standard deviation in ash, HHV, Na$_2$O, and K$_2$O, where data are available. Literature fecal sludge (FS) data from Gold *et al.* (2017); biofuel data from Phyllis2. Number of test replicates (*n*) varies by sample and test; *n* = 3 for Boulder ash, Na$_2$O, and K$_2$O and *n* = 1 for HHV. Sewage sludge *n* = 12–44; bagasse *n* = 7–16; coffee husk *n* = 2–4; sawdust *n* = 5–14 for various tests.

65 wt% fecal sludge and 30 wt% sawdust performed significantly better than pellets made with 53 wt% fecal sludge and 40% coffee husk. This is directly supported by a comparison of alkali indices: sawdust has a much lower alkali index than coffee husk, and can therefore support higher ratios of fecal sludge during cofiring. Fecal sludge can be tempered much further with sawdust than with coffee husk. Tukahirwa *et al.* (2016) attribute the clinker formation to technical errors, but the alkali indices could provide insight into the mechanism behind their observations.

In this chart, the literature biofuels have error bars spanning nearly the entire range, from 5–100% mass fraction biofuel. This demonstrates the large variation in properties for the samples within each biomass category. Standard deviations are 1–212% of the mean for these four fuel properties in Phyllis2. Relying on typical performance of a category to estimate performance of a specific fuel is not recommended, and the specific fuels should each be analyzed as budget allows. This explicitly includes fecal sludge, a fuel with large known variability and still little quantitative characterization data.

Similarly, while the alkali index can be a useful comparator of different fuels, the literature consensus is that fuel properties are insufficient to predict slagging and fouling in a boiler (Miles *et al.* 1995; Jenkins *et al.* 1998; Folgueras *et al.* 2005; Zevenhoven *et al.* 2012). The specific forms of alkalis, other inorganic contents (especially Cl, Si, and Ca), nonlinear ash fusion curves, mitigating effects of sulfation and high-phosphorus fuels (such as fecal sludge), and boiler design and operation can all increase or retard the formation of deposits. Fuels of interest should be tested at the pilot scale to understand the cumulative effect of these factors.

Chlorine corrosion

The mechanisms of high-temperature chlorine corrosion are discussed in (Salmenoja *et al.* 1999; Nielsen *et al.* 2000; Aho & Ferrer 2005; Shao *et al.* 2012). Figure 3 shows that chlorine levels in Boulder fecal sludge were spectacularly high, while Kampala and Dakar fecal sludge (Gold *et al.* 2017) was comparable with feces and sewage sludge. Notably, the maximum Cl reported in the Phyllis2 database for sewage sludge was 4.8%ds, but among the 38 samples, it is an outlier. Only one other outlier reports more than 0.3%ds Cl. One potential source of this chlorine in Boulder pits is the
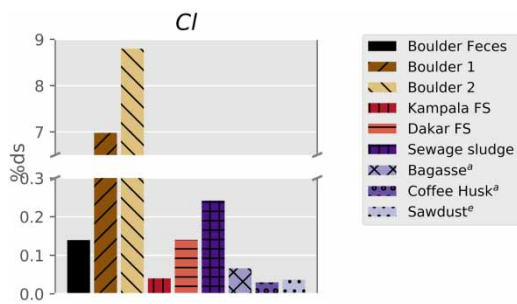
Figure 3 | Occurrence of Cl in fuels, reported as weight percent in fuel dry solids.
Sources: [a]Gold *et al.* (2017), [e]Phyllis2.

disposal of chlorinated cleaning products into the onsite containment system.

Keeping superheater temperatures low is a practical way to avoid high-temperature Cl-corrosion, and this has traditionally been done in biomass combustion (Nielsen *et al.* 2000). Nonetheless, care should be taken to test for chlorine in future fecal sludge studies to understand if these results are anomalous, as it is a major component in boiler corrosion.

Ash fusion temperatures

These values are reported in the Appendix. There are well-documented shortcomings with the repeatability and reliability of the ASTM1857M-04 test (Miles *et al.* 1995; Baxter *et al.* 1996;

Wall *et al.* 1998; Zevenhoven *et al.* 2012), and were therefore not used as predictors for slagging or fouling.

Fuel improvement measures

The high ash content and low HHV of fecal sludge make it interesting to investigate methods of fuel improvement in addition to co-processing with biomass. Two methods were investigated for improving the performance of the fuels: carbonization to increase HHV, and ash leaching to remove ash. While carbonization did not improve fuel quality, ash leaching provided moderate improvements.

Carbonization

In general, carbonization improves fuel quality by decreasing the oxygen and hydrogen, compared with carbon, as C-C bonds contain more energy than C-H or C-O (McKendry 2002). Additionally, briquettes with lower ratios of oxygen or hydrogen to carbon produce less CO_2, water vapor, and smoke during combustion, increasing efficiency (Ward *et al.* 2014). The expectation is that HHV will increase with carbonization. The results of carbonization of fecal sludge are shown in Figure 4.

Carbonization of the urine-diverted feces was somewhat beneficial, increasing the HHV 14% (to 23 MJ/kg) and carbon fraction by 12%, even though ash increased by 70%. These results are consistent with results of low
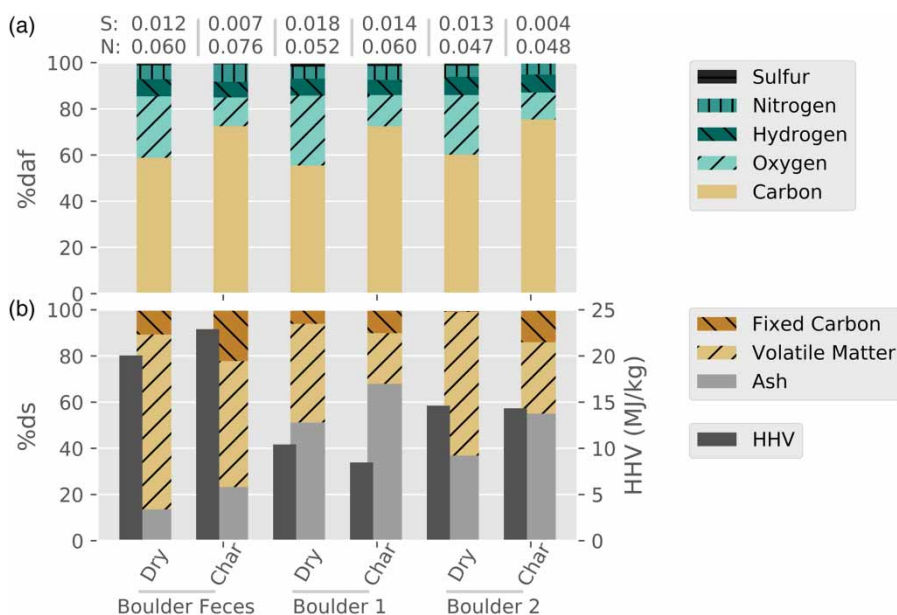

Figure 4 | Dried and carbonized fuels were analyzed for (a) ultimate, (b) proximate and HHV. Ultimate results are reported on a dry, ash-free basis (%daf), and proximate results are reported as percent dry solids (%ds) of the fuel; HHV is reported as MJ/kg on a secondary axis. F.C. denotes fixed carbon, V.M. denotes volatile matter.

temperature feces pyrolysis in Ward *et al.* (2014). In fecal sludge, carbonization reduced fuel carbon, oxygen, hydrogen, nitrogen, and sulfur fractions; ash was the only fraction that increased. The ratio of volatile matter to fixed carbon decreased from >7:1 to 2–2.5:1, as volatile matter is driven off at carbonization temperatures. The O/C and H/C ratios decreased slightly, improving the structure of the remaining organic fraction. However, these marginal gains came at a high price. Carbonization increased an already high proportion of ash by 41%, and decreased HHV 10% on average. Overall, carbonization did not yield improvement on the fecal sludge fuels.

Ash leaching

The energy content of the organic fraction of fecal sludge (when calculated on an ashless basis) is comparable to

biomass fuels; reducing the high ash content is desirable. As seen in Figure 5, leaching was highly productive for the fecal fuels, removing large fractions of ash (0.7–20%, average of 9%). While the full leaching procedure may be cost-or-energy-prohibitive, simply incorporating mechanical dewatering of fecal sludge (instead of evaporative drying) could reduce ash (up to 21%), increasing HHV by up to 1.25 MJ/kg (8%).

Ash leaching can also provide insight to the degree of reactivity of the components in the ash. Typically, in biomass, chlorine and alkali salts are water leachable, more reactive, and are associated with greater corrosion, slagging, and fouling in boilers (Miles *et al.* 1995; Zevenhoven *et al.* 2012). Figure 6 shows the soluble ash fractions of the fuel by solvent, as determined by the ash leaching procedure.

The water-soluble ash fraction of fecal sludge (8–21%) is comparable to switchgrass (15%) and high compared to
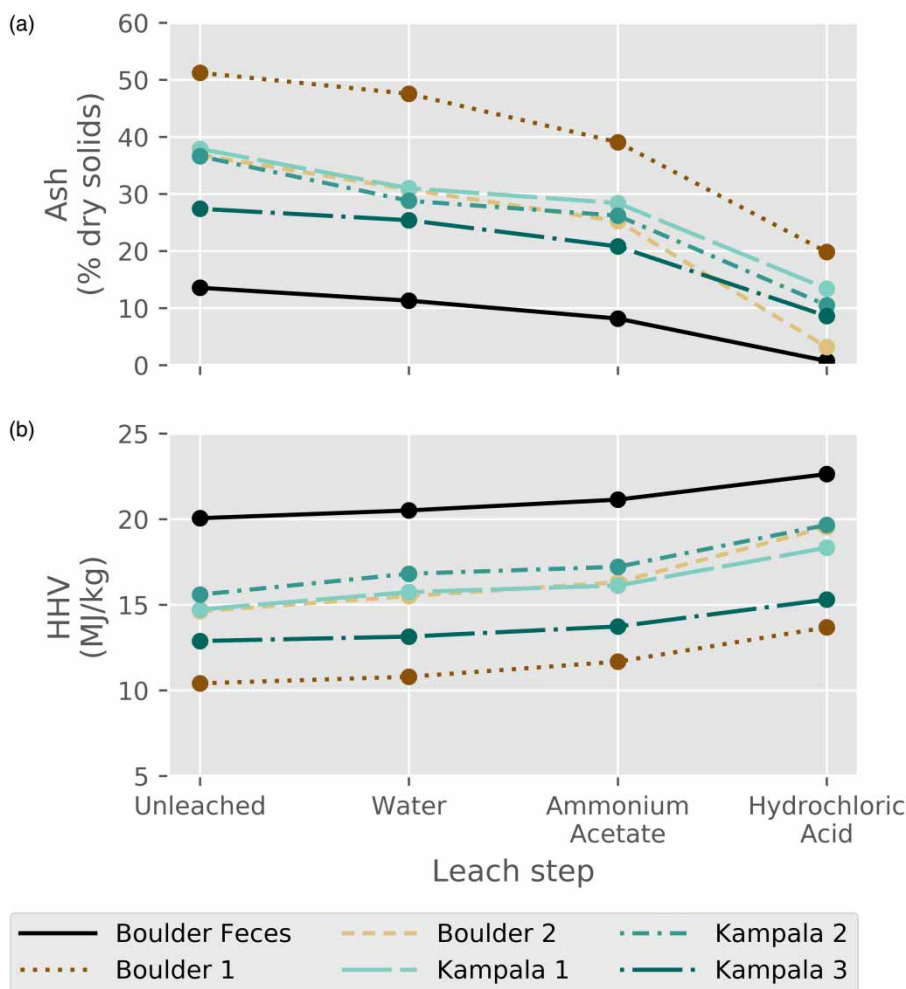

Figure 5 │ Effect of ash leaching on (a) ash fraction of the fuel and (b) calculated HHV.
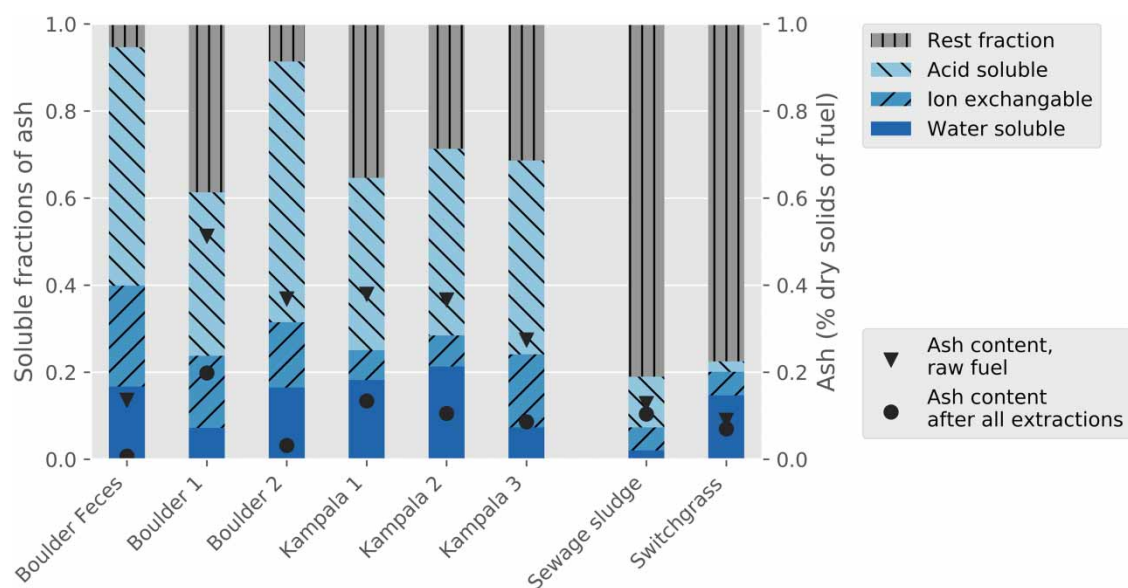
Figure 6 | Soluble fractions of ash are shown for the fecal fuels in this study, switchgrass (Miles *et al.* 1996) and sewage sludge (Zevenhoven *et al.* 2012).

sewage sludge (2%). Untreated, this implies greater slagging and fouling potential compared to sewage sludge, but similar potential compared to switchgrass. However, the water content of raw fecal sludge is typically higher than 95%, and much effort is currently focused on improving solid–liquid separation during fecal sludge treatment (Seck *et al.* 2015). If effective filtration- or compression-based dewatering could be incorporated into the fecal sludge treatment chain, then the water-soluble and potentially highly reactive fraction of the ash could be removed. This would improve the fuel, with the understanding that reducing the occurrence of these elements (especially K and Na) would increase the recommended cofire ratio.

CONCLUSIONS

1. This study is intended as a pathfinder in the characterization of fecal sludge as a fuel by extending assessment beyond routine calorimetry. Ash speciation and ash leaching allow fecal sludge to be subjected to the same level of scrutiny applied to other biofuels and inform the discussion of using fecal sludge as a fuel.
2. Ash speciation revealed high alkali concentrations, which could pose a slagging/fouling risk according to an alkali index commonly used for solid fuels. These findings support conclusions from previous pilot-scale trials that showed co-processing with biomass containing lower ash and higher HHV improved fecal sludge fuel performance. Characterization of ash fractions in fuels

allows the calculation of cofiring ratios to provide a starting framework for co-combustion trials. This in turn can provide helpful guidance when planning full-scale industrial reuse.

3. Water soluble ash accounted for up to 21% of the ash fraction in fecal sludge, and removing it could contribute 1.25 MJ/kg additional calorific value (an 8% increase). Incorporating improved filtration and mechanical dewatering during fecal sludge treatment could better remove dissolved inorganic materials, improving the energy value of treated fecal sludge. However, the energy consumed by dewatering must be carefully evaluated to ensure that it is not higher than the energy recovery benefit from ash reduction.
4. A limited effort at thermally upgrading fecal sludge samples by carbonization showed no improvement in heating value.
5. With a few exceptions, the study generally confirms that fecal sludge is in the same family as the broader class of solid biofuels. The valorization of this sanitation hazard and disposal problem into a beneficial energy resource deserves careful consideration and the further application of quantitative science.

ACKNOWLEDGEMENTS

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